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SIMPLIFIED LCA

Environmental assessment of sewage effluent disinfection system: electron beam, ultraviolet, and ozone using life cycle assessment

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Abstract

Purpose This study assesses the impacts of three different disinfection processes of sewage effluent, namely the electron beam (E-beam), ultraviolet (UV), and ozone systems, on the environment by using life cycle assessment (LCA).

Methods The LCA employed was the comparative LCA which consists of three parts according to life cycle stages. Electricity consumption was the reference flow that can yield 99% disinfection efficiency for microorganisms present in a 1×10^{5} $m^{3}day^{-1}$ sewage treatment plant effluent over 20 years.

Results The comparison of the LCA results indicated that the environmental impact of the UV disinfection system was the lowest, followed by the E-beam and ozone disinfection systems. The key issues of the E-beam, UV, and ozone disinfection systems are electricity consumption and SF_6 usage, electricity consumption and UV lamp, and electricity consumption and liquid oxygen feeding system, respectively.

Conclusions Electricity consumption is the key input parameter that determines the LCA results.

Keywords Disinfection · Electron beam · LCA · Ozone · UV

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1 Introduction

The effluent from a sewage treatment plant needs to be disinfected to prevent pathogenic microorganisms from entering the receiving bodies of water. Disinfection is a process that partially destroys disease-causing organisms (Chang et al. 1985; Galal-Gorchev 1996). Commonly used disinfection systems are the ultraviolet (UV) disinfection, ozone disinfection, and chlorine disinfection systems. Currently, the most widely used disinfection system in Korea for sewage treatment is the UV disinfection system. Of all domestic sewage treatment facilities, 76% employ the UV infection system and 19% employ the ozone system, while the remaining use miscellaneous systems. The chlorine disinfection system is primarily used for water supply treatment and is rarely used for sewage disinfection in Korea (MoCT 2005)

In general, the high operating and maintenance costs and high electricity consumptions of the UV and ozone disinfection systems are of concern to municipal governments and tax payers. Of most concern is their impact on the environment, especially, with respect to the minimization of greenhouse gas (GHG) emissions due to their use of energy consumption (electricity). This minimization can only be realized by employing an energy-efficient disinfection system.

A new disinfection system is currently being adopted in Korea, known as the electron beam accelerator, or electron beam (E-beam). The E-beam is a device that accelerates electrons using an electromagnetic field to emit electron beams at high speed. Since radioactive substances are not used as raw materials, E-beam is free from radioactivity. In addition, the E-beam is a ray of light, and thus it is irradiated by light under high-energy irradiation field conditions. It is expected that the E-beam will be an alternative to the

conventional disinfection systems because of its high efficacy in disinfecting microbes with relatively low amounts of energy consumption (Sampa et al. 1995; Kurucz et al. 1995). Since the size of the E-beam system is considerable and complex to operate compared to the conventional disinfection systems, it is not yet appropriate for use in small- or medium-sized sewage treatment plants. It is appropriate, however, for application in large-sized treatment plants. The advantages and disadvantages of the three disinfection systems are shown in Table 1.

When selecting a disinfection system for a sewage treatment plant, several aspects such as economy, technology, disinfection performance, and environment must be considered. All three disinfection systems are technically mature and reliable and are known to be competitive in terms of disinfection capability and capital as well as operating costs. Thus, the environmental aspect becomes of prime importance in this research, so disinfection performance, and technical and economic aspects were not considered.

The major objective of this research is to compare the environmental impacts of the different sewage disinfection systems at each life cycle stage and to determine the disinfection system that has the least impact on the environment.

Specifically, this research aims to quantify the energy consumptions, GHG emissions, and the environmental impact for several impact categories of the three disinfection systems at each life cycle stage. The quantified environmental impacts can be used by sewage treatment plant designers and operators to select and operate a disinfection system.

2 Methods

Disinfection efficiency is a function of the disinfectant dose and the contact time between the disinfectant and the microorganisms in the disinfection chamber. A higher dose and longer contact time yield greater disinfection efficiency.

Different types of disinfectants are used in the three disinfection systems: E-beam, UV, and ozone. The ozone disinfection system uses a chemical, while UV and E-beam disinfection systems use high-energy emitted in the form of ultraviolet light and electron flow, respectively. However, the basic driving force for all three systems is the same, i.e., electrical energy. Thus, electricity consumption was measured as a surrogate parameter of the disinfectant dosage. The dosage is defined by Eq. 1:

$$E=\frac{C_{\mathrm{Lr}}}{C_{\mathrm{id}}} \tag{1}$$

where, power is electric power in kilowatt, and time of irradiation is the duration of time of electric power applied to a given volume of sewage effluent, measured in hours.

Disinfection efficiency is defined by Eq. 2:

$$\Delta C=\frac{C_0-C}{C_0}\times 100 \tag{2}$$

where, C_0 and C represent the total coliform (*Escherichia coli*) concentration (colony forming unit) in the influent sewage and that in the effluent from the sewage treatment plant, respectively.

Disinfection efficiency data is required to determine the reference flow of the disinfection system. For the same effluent from a sewage treatment plant, the effective dosages of E-beam, UV, and ozone to achieve the same removal efficiency (C_0 to C) must be obtained by experiment. In order to determine the reference flow of the three disinfection systems, a laboratory scale disinfection experiment was performed using the same sewage treatment plant effluent. Particulars of the experimental conditions are defined below.

2.1 Experiments for the UV and ozone disinfection systems

Experiments for the UV and ozone disinfection systems were performed using batch reactors (1 L liquid volume) and the effluents from the sewage treatment plant at J city, Korea. The disinfection efficiencies were measured over a regular time interval by counting the total coliform bacteria of the effluent samples based on the spread plate method (Eaton et al. 2005). The electricity consumption by both systems in the experiments was directly measured using a power meter (HPM-300A, AD POWER, Korea).

One UV lamp (Philips, TL 6 W/05, 6 W electrical power, 210 mm length and 15 mm diameter) was used in the UV disinfection experiment. The UV lamp in a quartz tube (25 mm diameter×350 mm height) was placed in the center of a quartz reactor (100 mm diameter×200 mm height), which was wrapped with stainless steel to minimize the occurrence of other photo-oxidation processes. The UV lamp intensity was measured by the H_2O_2 actinometry (Glaze et al. 1995). For the ozone disinfection experiment, ozone was generated by using the LAB2B Model ozone generator (Ozone Engineering 2010); the ozone bubbled from the bottom of the reactor. By using pure oxygen gas, ozone was produced at the flow rate of 1.164 mg O_3 min^{-1}. The ozone concentration was analyzed by the KI wet chemistry test (Rakness et al. 1996).

2.2 Experiment for the E-beam disinfection

Batch experiments were performed using a system that consisted mainly of an accelerated E-beam source of 2.5 MeV with 50 mA current peak intensity (Kim 2007, personal communication). The aqueous samples (0.8 L) containing coliform bacteria on a glass plate (80×10×

Table 1 Advantages and disadvantages of the three disinfection systems

		E-beam	UV	Ozone
Additional function	Advantages	High efficacy and high performance against non-degradable organic matters	–	Excellent deodorizer and decolorizer, air saturation
	Disadvantages	–	–	–
Space	Advantages	–	Occupy less space	–
	Disadvantages	Occupy bigger space and more complicated to operate	–	Occupy some space
Contact time	Advantages	Short contact time offering stability with the fluctuating sewage flow rate	Short contact time	–
	Disadvantages	–	–	Relative long contact time
Chemical toxicity	Advantages	Non toxic	Non toxic	–
	Disadvantages	–	–	Toxic
Residual	Advantages	–	–	–
	Disadvantages	No residual	No residual	No residual
Cost	Advantages	Few maintenance cost for coolant	–	–
	Disadvantages	High initial investment	High maintenance cost for UV lamp	High initial investment and maintenance costs (e.g., high priced accessory required, high consumption of electricity)
Chlorine demand	Advantages	–	–	Reduce chlorine demand
	Disadvantages	No relation	No relation	–
Impact on ecosystems	Advantages	little impact	little impact	Less impact with ozone decomposition treatment
	Disadvantages	–	–	–
Efficiency	Advantages	High efficiency	–	–
	Disadvantages	–	Less efficiency in high turbidity condition	–

1 cm) were irradiated separately at 0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 1.0 kGy. The electricity consumption was calculated based on the irradiation intensity.

The electricity consumptions required to disinfect the bacteria (i.e., *E. coli*) in 1 L of sewage effluent to yield different removal efficiencies are listed in Table 2. The results indicate that, based on energy consumption, the UV disinfection system was the most effective in disinfecting bacteria in the sewage effluent, followed by the E-beam and ozone disinfection systems.

2.3 Modeling of the three disinfection systems

2.3.1 Goal definition

The purpose of this study is to compare the environmental performance of the three different sewage disinfection systems at each life cycle stage. The results are expected to provide guidance to sewage treatment plant designers in their selection of a suitable disinfection system for their treatment plants and to plant operators in their management of energy use and GHG emissions.

2.3.2 Function

The performance of each disinfection system is defined as the disinfection efficiency of waterborne microorganisms (in particular *E. coli*) present in the effluent of the sewage treatment plant. All disinfection systems are used to perform only disinfection.

2.3.3 Functional unit

The functional unit represents a function in a measurable unit (International Organization for Standardization; ISO 2006). Here, the functional unit is defined as the reduction efficiency of waterborne microorganisms under the same characteristics and flow rate (Q) of the sewage effluent undergoing disinfection over the same time period.

2.3.4 Reference flow

The reference flow measures the performance of the functional unit (ISO 2006). The functional unit and reference flow include duration of operation of the disinfection system. This measure enables a complete inventory of all the inputs and outputs of the disinfection system, such as the total number of equipment and consumables used including the number of UV lamps used during the lifetime of the disinfection system and the sewage treatment plant.

Since the Q of the effluent from most sewage treatment plants in Korea range from 5×10^4 to 5×10^5 $m^3 day^{-1}$, and the lifetime of these plants is 20 years without a major overhaul, Q of 1×10^5 $m^3 day^{-1}$ and a lifetime of 20 years were chosen to define the reference flow (MoE 2008). The reduction efficiency was chosen to be 99% based on the experimental data gathered in this study and the governmental regulation on the *E. coli* counts in a sewage treatment plant effluent (MoE 2008).

The reference flow of a disinfection system was defined as the electricity consumption requirement to achieve 99% reduction efficiency of *E. coli* in a sewage treatment plant that operates at a flow rate of 1×10^5 $m^3 day^{-1}$ and whose lifetime of 20 years. For simplicity and for avoidance of large numbers, the reference flow in this paper was expressed as electricity consumption/sewage flow of 1 day rather than of 20 years. However, the system boundary encompasses the entire 20 years of plant life so that all inventory data gathered in this study applies for the 20-year period.

Table 2 Electricity consumption rates for disinfection efficiencies of the total coliform bacteria

Unit: Wh/L

Treatment -log (C/C_0)	E-beam	UV	Ozone
2 (99%)	0.210	0.044	1.430
3 (99.9%)	0.400	0.052	2.700

2.3.5 System boundary setting

In principle, the system boundary of each disinfection system should span an entire life cycle stage. However, for practicality, only the major processes and activities are included in the system boundary for the analysis of the environmental impacts of the disinfection systems. The major processes and activities within a system boundary include the upstream processes and the manufacturing stage including parts, and the use and end-of-life stages.

2.3.6 Upstream processes and manufacturing stage of each disinfection system

The major parts as well as their material composition and weights of the three disinfection systems are listed in Table 3.

The use stage scenario of each disinfection system is based on the 20-year lifetime. The key parameters of the use stage scenario include the use stage electricity consumption and maintenance. The end-of-life scenario is based on the following assumptions.

Data was collected for the collection, treatment, and disposal of consumables. The disinfection equipment, including spare parts for maintenance, were not considered because each system was assumed to last 20 years and the end-of-life stage impact on the spare parts will be minor compared to the total impact of each disinfection system.

Table 3 Major parts of the three disinfection systems

Part list	Materials	Weight (kg)	wt.%	Cumulative wt.%
E-beam				
Shielding facility (steel)	Steel	25,740	85.63	85.63
Gas system	STS[a] 304	2,407	8.01	93.63
Secondary winding	Cu: 450 STS 304: 200 Epoxy: 30	680	2.26	95.90
Cyl. magnetoguide	Steel	265	0.88	96.78
Ion pump	STS: 80 Permanent magnet: 120 Ti: 10	210	0.70	97.48
Disk magnetoguide	Epoxy: 40 Steel: 150 Insulating paper:10	200	0.67	98.14
Extraction system	STS 304	200	0.67	98.81
Primary winding	Cu: 49.2 STS 304: 8.2 Epoxy: 106.6	164	0.55	99.35
Accelerating tube	STS 304	85	0.28	99.63
Screening ring	Cu	60	0.20	99.89
Water distributor	STS 304	20	0.07	99.90
Others(cut-off)		30	0.10	100.00
	Total	30,061	100.00	
UV				
Quartz sleeve	Pure quartz	230	19.79	19.79
ballast 92	Painted Sheet Steel	200	17.21	37.01
Flood gate	STS 304	160	13.77	50.77
Lubricant (ml)		120	10.33	61.10
UV lamp	UV Glass	100	8.61	69.71
Junction box	STS 304	86	7.40	77.11
Hoist	SS[b]400	85	7.31	84.42
Sensor establish bracketing	STS 304	50	4.30	88.73
Pneumatic cylinder	Coated Aluminum	30	2.58	91.31
Module frame	STS 316	24	2.07	93.37
UV module	STS 316	24	2.07	95.44
Automatic washing equipment	STS 316	16	1.38	96.82
Shaft	STS 304	12	1.03	97.85
Establish bracketing	STS 304	10	0.86	98.71
Bevel gear	STS 304	8	0.69	99.40
Gearbox	PhBr	4	0.34	99.74
Perception part	STS 304	2	0.17	99.91
Others(cut-off)		1	0.09	100.00
	Total	1,162	100.00	
Ozone				
Oxygen storage tank	STS 304, SB 41	3,400	60.70	60.70
Chamber and etc.	STS 304	346	6.18	66.88
Catalytic towel	STS 304	320	5.71	72.59
Air storage tank	SB 41	240	4.28	76.88
Carburetor	A6063[c], STS 304	220	3.93	80.81
Ozone destruction	STS 304	210	3.75	84.56

Table 3 (continued)

Part list	Materials	Weight (kg)	wt.%	Cumulative wt.%
Shell plate and chamber	STS 304	202	3.61	88.16
Control panel	SS400	95	1.70	89.86
Support lug and base plate	SS400	82	1.46	91.32
Gas Feeding system	STS 304	70	1.25	92.57
Fan	STS 304	60	1.07	93.64
H.V. transformer and inverter	PVC	60	1.07	94.72
Mesh screen	PE	58	1.04	95.75
Ground electrode	STS 316	43	0.77	96.52
Desiccant dryer	STS 304	40	0.71	97.23
Ozone injection control flow meter 35A	STS 304	32	0.57	97.80
Refrigerated air dryer	STS 304	30	0.54	98.34
Ozone injection control flow meter 25A	STS 304	27	0.48	98.82
Dielectric tube	Borosilicate	23	0.41	99.23
Body	SS400	15	0.27	99.50
Air filter 1U	STS 304	10	0.18	99.68
Air filter 5U	STS 304	10	0.18	99.86
Pin	Cu	2	0.04	99.89
Others(cut-off)		6	0.11	100.00
	Total	5,601	100.00	

[a] STS 304/316 are Korean Standard symbols equivalent to SA-182F 304/F 316 of ASTM, respectively

[b] SB41 is a Korean Standard symbol equivalent to SA-283 Gr. C/D of ASTM

[c] A6063 is a Korean Standard symbol equivalent to SB-221 6063 of ASTM

Only the consumables are replaced and treated at the end of the life cycle stage. In this research, depleted UV lamps were the only consumables.

The process trees of the three disinfection systems are shown in Fig. 1a–c. The process tree was developed by combining the upstream processes and manufacturing stage with the use and end-of-life stage scenarios. All the parts listed in Table 3 were included in the process tree; where cutoff at 99.9% was made of the identified parts. This does not imply that all the possible parts in the disinfection system were included.

2.3.7 Types and sources of data

Input and output data to and from each disinfection system is the onsite data for the use stage. For the use of raw materials (upstream processes), the manufacturing stage and the end-of-life cycle stage, the input and output data is literature data, obtained mainly from BUWAL 250 LCI database (Spriensma 2004).

2.3.8 Data quality requirements

Geographical coverage, temporal coverage, and technology coverage are those for Korea within 5 years of data, and recent technologies, respectively. Missing data or a data gap was treated as no data. No assumptions were made to fill in the missing data or data gap.

2.3.9 Allocation procedure

No allocation was applied to the study.

2.3.10 Impact categories

The impact categories considered were carcinogens, respiratory effects on humans caused by organic substances, respiratory effects on humans caused by inorganic substances, climate change, radiation which includes photochemical oxidants creation (e.g., smog), ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, and minerals. The unit of assessment was disability adjusted life year for the first six impact categories, potentially affected fraction for ecotoxicity, potentially disappeared fraction for acidification and eutrophication, and mega joule surplus for minerals (Goedkoop and Spriensma 2001a).

2.3.11 Life cycle impact assessment methodology

The life cycle impact assessment (LCIA) methodology used follows the standard method in ISO 14044. Since this study

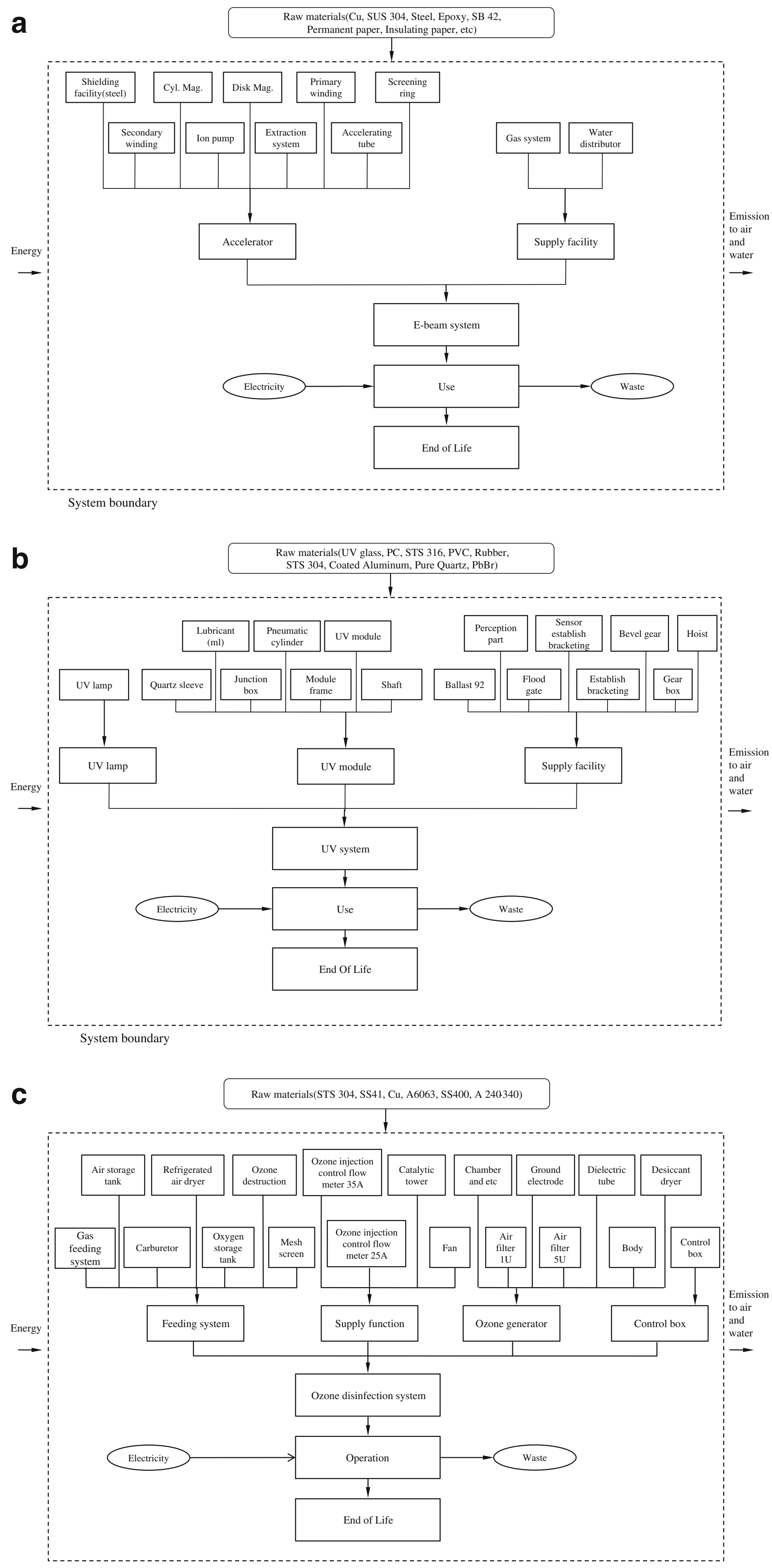

Fig. 1 **a** Process tree of the E-beam disinfection system. **b** Process tree of the UV disinfection system. **c** Process tree of the ozone disinfection system

uses the comparative life cycle assessment (LCA), only the mandatory elements of the LCIA were assessed (ISO 2006). The Eco-indicator 99 methodology was used to calculate the weighted results of the disinfection system (Goedkoop and Spriensma 2001b).

The global warming potential (GWP) value of the GHGs including CO_2, CH_4, N_2O, CH_2FCF_3, CHF_3, CF_4, C_2F_6, and SF_6 for a 100-year time horizon are 1, 25, 298, 1,430, 14,800, 7,390, 12,200, and 22,800 g CO_2 equivalent, respectively (IPCC 2007).

2.3.12 Interpretation methods

The interpretation includes a contribution analysis for the identification of the key parameters and a sensitivity analysis of the identified key parameters. The sensitivity analysis follows the method proposed by Schmidt and Beyer (1999). In this method, elasticity is calculated by Eq. 3. If the elasticity is >1, the parameter for the sensitivity analysis is judged as sensitive, but <1, it is judged as less sensitive. When the parameter is judged as sensitive, new data for the parameter is sought to ensure the accuracy of the LCA results through accurate data of the identified key parameters.

$$E = \frac{C_{\mathrm{Lr}}}{C_{\mathrm{id}}} \tag{3}$$

Where,

E the elasticity
C_{Lr} change of LCA result
C_{id} change of input data

$$C_{\mathrm{id}} = \frac{D_{\mathrm{Ni}} - D_{\mathrm{oi}}}{D_{\mathrm{oi}}} \times 100(\%) \tag{4}$$

Where,

D_{Ni} new input data
D_{Oi} original input data

$$C_{\mathrm{Lr}} = \frac{R_N - R_o}{R_o} \times 100(\%) \tag{5}$$

Where,

R_N new LCA result
R_{O} original LCA result

3 Results and discussion

3.1 Results from experiments and LCA study

Electricity consumption per liter of effluent to achieve 99% and 99.9% disinfection efficiencies were estimated for the E-beam, UV, and ozone systems from Fig. 2, respectively, and are shown in Table 2. From the data in Table 2, the UV disinfection system consumes the least amount of electricity, followed by the E-beam and ozone disinfection system.

The results of the experimental studies for the three disinfection systems are shown in Fig. 2 as the disinfection efficiencies versus electricity consumption per 1 L of effluent.

The reference flows of the E-beam, UV, and ozone disinfection system are expressed as electricity consumptions. The reference flow was calculated by multiplying the electricity consumption per liter for the 99% disinfection efficiency in Table 2 and the Q of 1×10^5 $m^3 day^{-1}$ and a lifetime of 1 day. The reference flows of the E-beam, UV, and ozone disinfection systems per 1 day sewage flow were 2.10E+04 kWh/(1×10^5 m^3), 4.40E+03 kWh/(1×10^5 m^3), and 1.43E+05 kWh/(1×10^5 m^3), respectively.

The maintenance required for the E-beam system was SF_6: 259.9 kg and Ti: 0.42 kg; for the UV system, 2,000 UV lamps; and for the ozone system nothing

The results of the LCA study for the three disinfection systems are arranged into four categories: (1) energy consumption in the use stage, (2) GHGs emissions and global warming impact, (3) environmental impact on the impact categories, (4) and key issues identified for each life cycle stage. For each category, not only the key findings but also discussions on the key findings are presented. In addition, the limitations of this study are discussed.

3.2 Energy consumption in the use stage and economic aspects

The use stage electricity consumption was calculated by multiplying 20 years of lifetime to the reference flow of each disinfection system. Thus, the energy consumption during the use stages of the E-beam, UV, and ozone disinfection systems for 20 years of operation are 1.53E+05 MWh, 3.21E+04 MWh, and 1.04E+06 MWh, respectively. Considering that the only source of the energy consumption is electricity and approximately 0.46 kg of CO_2 is emitted from the 1 kWh of electricity (Lee et al. 2004), the amounts of CO_2 emission from the E-beam, UV, and ozone disinfection systems are 7.05E+04, 1.48E+04, and 4.80E+05 t, respectively. These are considerable amounts of CO_2 emission. The energy consumption and the CO_2 emission of the E-beam disinfection system are approximately 4.76 and 0.15 times, respectively, those of the UV and ozone

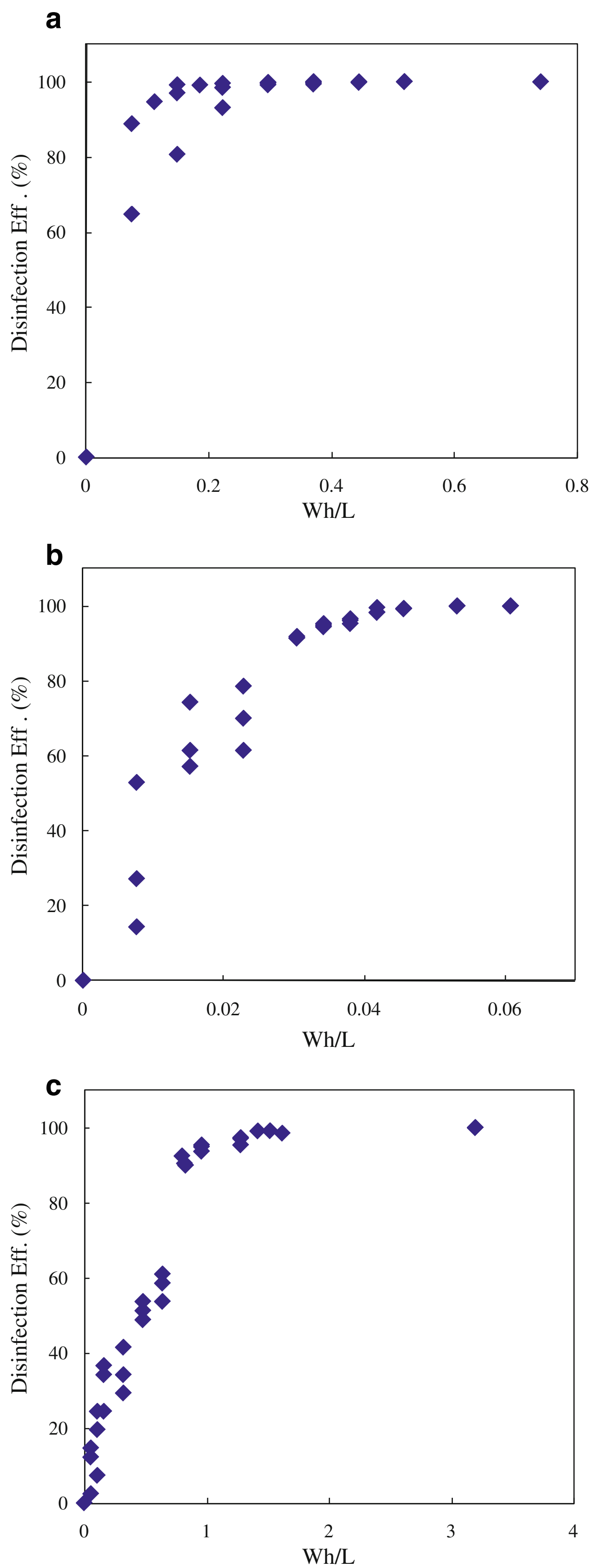

Fig. 2 Disinfection efficiencies of the total coliform bacterial in wastewater effluent by E-beam (**a**), UV (**b**), and ozone (**c**)

disinfection systems, respectively. Thus, the electricity consumption and CO_2 emission were the least in the UV disinfection system, followed by the E-beam and ozone disinfection system.

No vigorous analysis of the economic aspects of the three disinfection systems was conducted. However, comparable amount of electricity consumption which is the major source of the operating cost for the three disinfection systems indicates that the E-beam disinfection system could be economically competitive. Excellent disinfection performance as well as recalcitrant chemicals removal efficiencies (Liltved and Landfald 2000; Cho 2005) suggest that E-beam disinfection technology can be envisaged as a viable alternative to the conventional disinfection technologies not only technically and environmentally but also economically from the energy consumption perspective. In order to reach definite conclusion about the economic aspects of the E-beam disinfection system, however, a rigorous economic analysis should be performed including the life cycle cost analysis.

3.3 GHGs emissions and global warming impact

In order to specifically address the climate change issue, GHGs emissions including CO_2 of the three disinfection systems were identified and the impact of their GHGs emissions on global warming was assessed. Table 4 lists the inventory results of the GHGs emissions and their impact on global warming.

Table 4 shows that the global warming impact of the E-beam disinfection system is approximately 5.02 and 0.16 times those of the UV and ozone disinfection systems in the use stage, respectively, and that the use stage is the dominant stage. This follows a similar trend as for the case of the CO_2 emission. That is, the global warming impact is the least in the UV disinfection system, followed by the E-beam and ozone disinfection systems.

A comparison between the global warming impact values and the CO_2 emission values of the three disinfection systems indicates that there are GHGs other than CO_2 emitted from the E-beam disinfection system. Notably, the use of SF_6 by the E-beam system has a significant global warming impact, while the use of other GHGs in the other disinfection systems has a low to negligible impact.

3.4 Environmental impact on the impact category

The impact of the three disinfection systems on the impact categories was assessed by calculating the characterized impact. Table 5 shows the characterized impact results of the three disinfection systems in their entire life cycle stages. For three disinfection systems, the use stage is the dominant stage. With the exception of the impact categories of radiation, land use, and minerals, the impact of the UV

Table 4 GHGs emission inventory results and the global warming impact of the three disinfection systems (ton GHGs and ton CO_2-eq for the GWP)

GHGs	E-beam		UV		Ozone	
	GHGs emission	GW impact	GHGs emission	GW impact	GHGs emission	GW impact
At the manufacturing stage						
CO_2	4.22E+01	4.22E+04	2.34E+01	2.34E+01	2.22E+01	2.22E+01
Methane	5.28E−03	1.32E−01	4.68E−02	1.17E+00	3.34E−03	8.36E−02
N_2O	1.97E−05	5.86E−03	3.45E−04	1.03E−01	5.27E−05	1.57E−02
HFCs	6.73E−10	9.62E−07	7.42E−07	1.06E−03	–	–
PFCs	6.15E−08	4.87E−04	6.35E−06	7.44E−02	5.14E−04	4.05E+00
SF_6	2.28E−10	5.20E−06	3.74E−06	8.54E−02	–	–
Total		4.24E+01		2.49E+01		2.64E+01
At the use stage						
CO_2	6.57E+04	6.57E+04	1.42E+04	1.42E+04	4.48E+05	4.48E+05
Methane	1.56E+02	3.89E+03	3.35E+01	8.37E+02	1.06E+03	2.65E+04
N_2O	6.35E−01	1.89E+02	1.40E−01	4.17E+01	4.32E+00	1.29E+03
HFCs	6.22E−08	8.90E−05	1.48E−05	2.11E−02	–	–
PFCs	1.08E−07	8.49E−04	8.80E−05	1.03E−00	–	–
SF_6	2.61E−01	5.96E+03	2.13E−05	4.87E−01	–	–
Total		7.58E+04		1.51E+04		4.75E+05
At the EoL stage						
CO_2	−4.36E+01	−4.36E+01	−1.07E+00	−1.07E+00	−1.71E+01	−1.71E+01
Methane	−2.24E−01	−5.61E+00	−5.87E−03	−1.47E−01	−5.48E−02	−1.37E+00
N_2O	−7.67E−05	−2.29E−02	1.38E−05	4.11E−03	−7.10E−05	−2.12E−02
HFCs	–	–	–	–	–	–
PFCs	–	–	–	–	−6.23E−04	−4.61E+00
SF_6	–	–	–	–	–	–
Total		−4.93E+01		−1.22E+00		−2.31E+01
For life cycle						
CO_2	6.57E+04	6.57E+04	1.42E+04	1.42E+04	4.48E+05	4.48E+05
Methane	1.55E+02	3.89E+03	3.35E+01	8.38E+02	1.06E+03	2.65E+04
N_2O	6.35E−01	1.89E+02	1.40E−01	4.19E+01	4.32E+00	1.29E+03
HFCs	6.29E−08	8.99E−05	1.55E−05	2.22E−02	–	–
PFCs	1.69E−07	1.34E−03	9.44E−05	1.11E+00	−1.09E−04	−5.57E−01
SF_6	2.61E−01	5.96E+03	2.51E−05	5.72E−01	–	–
Total		7.58E+04		1.51E+04		4.75E+05

disinfection system is negligible compared with those of the E-beam and ozone disinfection systems at the use stage. For all the impact categories except radiation, land use, and minerals, the impact caused by the ozone disinfection system was significantly greater than that by the two other systems at the use stage. The impact caused by the E-beam disinfection system was in the middle between those of the UV and ozone disinfection systems at the use stage.

The results in Table 5 indicate that the UV disinfection system had the least impact on the most number of impact categories, followed by the E-beam and ozone disinfection systems at the use stage. Similar trends were observed for electricity consumption (CO_2 emissions) and global warming impact, where the UV disinfection system had the least impact, followed by the E-beam and ozone disinfection systems. From these results, the UV disinfection system is judged to cause the least impact, followed by the E-beam and ozone disinfection systems.

In the mineral impact category, the impact caused by the E-beam disinfection system was the greatest impact of the three disinfection systems through entire life cycle. Most of the impact on minerals resulting from the E-beam disinfection system occurred during the manufacturing stage. Table 6 shows the values of the minerals impact by the E-beam disinfection system.

3.5 Key issues identified

Contribution analysis of the life cycle impact results of the three disinfection systems shown in Table 7 revealed that electricity consumption in the use stage was the most

Table 5 Characterized impact of the three disinfection systems

Impact category	Unit	Manufacturing			Use			EoL			Entire life cycle		
		E-Beam	UV	Ozone	E-Beam	UV	Ozone	E-Beam	UV	Ozone	E-Beam	UV	Ozone
Carcinogens	DALY	1.44E−04	7.04E−04	3.87E−04	2.66E+00	5.72E−01	1.81E+01	−3.02E−03	−2.03E−05	−7.52E−04	2.66E+00	5.73E−01	1.81E+01
Resp. organics	DALY	4.35E−05	4.29E−05	1.30E−05	5.17E−02	1.12E−02	3.52E−01	−2.01E−05	−2.22E−05	−2.41E−05	5.17E−02	1.12E−02	3.52E−01
Resp. inorganics	DALY	3.90E−02	8.76E−03	1.38E−02	2.00E+01	4.31E+00	1.36E+02	−3.34E−03	−3.50E−04	−6.35E−03	2.00E+01	4.31E+00	1.36E+02
Climate change	DALY	8.76E−03	4.95E−03	5.37E−03	1.52E+01	3.00E+00	9.45E+01	−9.82E−03	−2.42E−04	−4.58E−03	1.52E+01	3.00E+00	9.45E+01
Radiation	DALY	1.44E−09	2.98E−06	–	1.26E−06	5.90E−05	–	–	–	–	1.26E−06	6.20E−05	–
Ozone layer	DALY	9.68E−08	1.40E−06	5.17E−07	1.17E−02	2.47E−03	7.96E−02	−3.91E−06	−2.32E−07	−5.17E−06	1.17E−02	2.47E−03	7.96E−02
Ecotoxicity	PAF×m^2 year	1.24E+03	8.75E+02	3.20E+02	2.68E+06	5.80E+05	1.83E+07	−1.02E+03	4.91E+01	−4.67E+02	2.68E+06	5.81E+05	1.83E+07
Acidification/Eutrophication	PDF×m^2 year	2.14E+03	7.66E+02	6.38E+02	1.17E+06	2.57E+05	7.96E+06	−3.21E+02	−9.17E+01	−2.69E+02	1.17E+06	2.58E+05	7.96E+06
Land use	PDF×m^2 year	2.71E+03	1.31E+03	8.51E+02	1.88E+01	2.51E+04	–	–	–	–	2.72E+03	2.64E+04	8.51E+02
Minerals	MJ surplus	2.98E+04	2.12E+03	6.88E+03	6.16E+01	2.03E+04	–	−1.82E+03	−3.57E+01	−3.13E+03	2.80E+04	2.24E+04	3.74E+03

DALY disability adjusted life year, *PAF* potentially affected fraction, *PDF* potentially disappeared fraction, *MJ* mega joule

Table 6 Impact values on minerals of the E-beam disinfection system

Impact category	Unit	Total	Stage		
			Manufacturing (%)	Use (%)	EoL (%)
Minerals	MJ surplus	2.80E +04	2.98E+04 (106.29)	6.16E+01 (0.22)	−1.82E+03 (−6.51)

dominant impact among the impact categories assessed excluding radiation, land use, and minerals. For these three remaining impact categories, the dominant sources of the impact were SF_6 for the E-beam system, UV lamp for the UV system, and no impact estimated for the ozone disinfection system. Therefore, the key issues identified are as follows: electricity consumption and SF_6 usage in the use stage, shielding facility and secondary winding in the manufacturing stage, recycling steel in the EoL stage for the E-beam disinfection system, electricity consumption and UV lamp in the use stage, UV lamp in the manufacturing stage, and electricity consumption in the EoL stage for the UV disinfection system, and electricity consumption in the use stage, liquid oxygen feeding system in the manufacturing stage, and recycling steel in the EoL stage for the ozone disinfection system. Table 8 shows the contribution analysis results for the identification of the key processes and key activities during the manufacturing stage of the E-beam disinfection system. The key process contributing to the impact on land use is the shielding facility and that contributing to the impact on minerals is the secondary winding.

The identified key processes and activities should be the targets of redesign and operation if the impacts due to the disinfection systems are to be reduced. Therefore, parts including secondary winding and shielding facility of the E-beam disinfection system should be redesigned. In addition, approximately 12% of the total global warming impact will be reduced if the existing SF_6 is replaced by a refrigerant that does not contribute to global warming. Thus, a new refrigerant should replace the existing SF_6 during the operation of the E-beam device.

However, at present, there are no firmly established alternative technologies replacing SF_6 in the E-beam disinfection system yet or reducing its emission to the atmosphere. Possible alternatives include the use of silicon oil applied to the circuit breaker for an insulation material (van der Zel 2003) in lieu of SF_6 and/or improvement of capture efficiency of SF_6 emission (Ghodke et al. 2007) from the E-beam disinfection system (Kim 2012, personal communication).

3.6 Sensitivity analysis

Electricity consumption in the use stage is the most important key issue (see Table 7). Therefore, electricity

Table 7 Contribution analysis of the three disinfection systems

Impact category	Manufacturing			Use			EoL			Entire life cycle		
	E-beam Process %	UV Process %	Ozone Process %	E-beam Process %	UV Process %	Ozone Process %	E-beam Process %	UV Process %	Ozone Process %	E-beam Process %	UV Process %	Ozone Process %
Carcinogens	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	89.1	98.0	97.6	100.0	97.8	100.0	26.9	414.0	14.4	100.0	97.7	100.0
Resp. organics	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	85.5	97.2	59.3	100.0	96.8	100.0	81.6	7.17	9.1	100.0	96.6	100.0
Resp. inorganics	Gas system	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	33.3	73.4	46	100.0	97.5	100.0	182.0	84.1	12.8	99.8	97.3	100.0
Climate change	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	62.9	91.8	78.8	91.1	97.3	100.0	72.0	87.5	20.6	91.1	97.2	100.0
Radiation	Disk magnetoguide	UV lamp	–[a]	SF_6	UV lamp	–[a]	–[a]	–[a]	–[a]	SF_6	UV lamp	–[a]
	100.0	98.9		100.0	100.0					99.4	99.9	
Ozone layer depletion	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	84.3	99.3	98.4	100.0	99.3	100.0	42.6	175	4.3	100.0	99.3	100.0
Ecotoxicity	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	92.1	96.6	83.4	100.0	97.2	100.0	84.3	105	24.5	100.0	97.1	100.0
Acidification/ eutrophication	Shielding facility	UV lamp	Liquid oxygen feeding system	Electricity	Electricity	Electricity	Recycling steel	Electricity	Recycling steel	Electricity	Electricity	Electricity
	49.1	88.7	54.9	100.0	95.7	100.0	165.8	20.1	26.4	99.8	95.5	100.0
Land use	Shielding facility	UV lamp	Liquid oxygen feeding system	SF_6	UV lamp	–[a]	–[a]	–[a]	–[a]	Shielding facility	UV lamp	Electricity
	72.1	96.0	83.2	99.6	100.0					71.6	99.8	49.4
Minerals	Secondary winding	UV lamp	Liquid oxygen feeding system	SF_6	UV lamp	–[a]	Recycling steel	Recycling steel	Recycling steel	Secondary winding	UV lamp	Liquid oxygen feeding system
	58.2	48.0	48.3	99.9	100.0		1.3	1.25	0.1	61.9	95.2	88.7

[a] No impact occurred

Table 8 Contribution analysis of the manufacturing stage of the E-beam disinfection system

Impact category	Unit	Total of the life cycle stage	Total of the manufacturing stage (%)	Part list: Accelerating tube (%)	Cylinder magneto guide (%)	Disk magneto guide (%)	Extraction system (%)	Iron pump (%)	Primary winding (%)	Screening ring (%)	Secondary winding (%)	Shielding facility (steel; %)	Water distributor (%)	Gas system (%)
Land use	PDF×m^2 year	2.72E+03	2.71E+03 (99.3)	5.32E+00 (0.2)	2.01E+01 (0.7)	1.32E+01 (0.5)	1.25E+01 (0.5)	5.72E+00 (0.2)	4.81E+01 (1.8)	5.69E+01 (2.1)	4.40E+02 (16.2)	1.95E+03 (71.6)	1.25E+00 (0.0)	1.51E+02 (5.5)
Minerals	MJ surplus	2.80E+04	2.98E+04 (106.3)	2.16E+02 (0.8)	1.25E+01 (0.0)	7.24E+00 (0.0)	5.09E+02 (1.8)	2.04E+02 (0.7)	1.86E+03 (6.6)	2.25E+03 (8.0)	1.74E+04 (61.9)	1.22E+03 (4.3)	5.09E+01 (0.2)	6.12E+03 (21.8)

consumption was chosen as the input data parameter for the sensitivity analysis. Since electricity consumption is a measured value, it has no uncertainty. Instead, electricity consumption depends heavily on the disinfection efficiency. Thus, electricity consumption for the disinfection efficiencies of 99% and 99.9% were tested in the sensitivity analysis. Electricity consumption for 99% disinfection efficiency was the initial data and that of 99.9% is the new data here.

Elasticity of 1.0 implies that there is a direct proportional relationship between the input data and the LCA results. When elasticity is <1, change in the input data is less sensitive to the change in the LCA results, and vice versa. When there is no relationship between the input data and the LCA results, there is no elasticity.

Results of the sensitivity analysis in Table 9 show that electricity consumption does not affect the radiation, land use, and minerals impact categories of the three disinfection systems (i.e., no relationship exists). For the ozone disinfection system, electricity consumption is directly proportional to the magnitude of the impact. For the UV disinfection system, a similar relationship exists, except for the climate change impact category. For the E-beam disinfection system, however, the elasticity in all impact categories was less than 1. Elasticity less than 1 indicates that there are inputs other than electricity consumption affecting the impact categories. Thus, the sensitivity analysis results indicate that electricity consumption is the key input parameter that determines the LCA results, here, the impact results. In order to reduce the impact of a disinfection system, electricity consumption should be controlled to meet the required disinfection efficiency.

Table 9 Elasticity of electricity consumption of the three disinfection systems

Impact category	E-beam (0.40 Wh/L instead of 0.21 Wh/L)	UV (0.052 Wh/L instead of 0.044 Wh/L)	Ozone (2.70 Wh/L instead of 1.43 Wh/L)
Carcinogens	0.973	1.001	1.000
Resp. organics	0.963	1.000	1.000
Resp. inorganics	0.970	0.998	1.000
Climate change	0.968	0.911	1.000
Radiation	0.000	0.000	–
Ozone layer depletion	0.990	1.000	1.000
Ecotoxicity	0.967	1.000	1.000
Acidification/eutrophication	0.951	0.998	1.000
Land use	0.000	0.000	0.000
Minerals	0.000	0.000	0.000

3.7 Comparison with other E-beam disinfection systems

Disinfection studies using E-beam accelerator technologies were made by Sampa et al. (1995) and Kurucz et al. (1995). As shown in Table 10, differing amount of irradiation dose resulted in different levels of disinfection efficiencies. Irrespective of the types of wastewater and treatment plant capacities, it can be observed that higher irradiation dosage achieves higher disinfection efficiencies. However, due to different samples for disinfection, ranging from sewage effluent to sludge, a direct comparison cannot be made. Nonetheless, Table 10 indicates that E-beam accelerator can be a viable and practical technology for the disinfection of microorganisms in the wastewater and sewage sludge.

Table 10 Comparison of disinfection performances using E-beam accelerator technologies

		This paper	Sampa et al. (1995)	Kurucz et al. (1995)
Accelerator information	Power (kW)	125	37.5	75
	Applied irradiation dose range (kGy)	0–1.0	2.0–10	4.0~
Disinfection performance information	Target	Sewage effluent	Lagoon system effluent	2–8% digested sludge
	Treatment capacity (m^3/day)	1.0E+05	7.2E+01	6.5E+02
	Irradiation dose (kGy)	0.15	2	4
	Achieved disinfection efficiency (%)	95	99.6	(Less than 10 total coliforms/100 g)
	Sample taken from	Jeong-eup city wastewater treatment facility, Jeong-eup, Korea	Sao Paulo Municipal Wastewater Treatment Plant, Sao Paulo, Brazil	Miami Virginia Key Wastewater Treatment Plant, Florida, USA

4 Conclusions

The E-beam disinfection is a new disinfection technology and can be a viable disinfection option from the environmental and technological aspects. No definite conclusion can be made as to the economic aspects; however, energy consumption during the operation or use of the E-beam disinfection system can be competitive compared with the UV and ozone disinfection systems.

Key issues of the E-beam, UV, and ozone disinfection systems were electricity consumption and SF_6 usage in the use stage, electricity consumption in the use stage and UV lamp in the manufacturing stage, and electricity consumption in the use stage and liquid oxygen feeding system in the manufacturing stage, respectively. The sensitivity analysis results indicated that electricity consumption was the key input parameter that determined the LCA results.

The UV disinfection system was judged to have the least impact on the environment, followed by the E-beam and ozone disinfection systems. The impact level of the E-beam disinfection system was in the middle between those of the UV and ozone disinfection systems, except for the minerals impact category where the E-bean disinfection system had the greatest impact among the three disinfection systems.

The E-beam disinfection system consumed more energy (i.e., electricity) and emitted more GHGs than the UV disinfection system. Meanwhile, the E-beam disinfection system consumed less energy and emitted less GHG than the ozone disinfection system. The major weak point of the E-beam disinfection system was the system's impact on minerals. The secondary winding and shielding facility were identified as the key manufacturing processes requiring redesign or, at the least, improvement. The use of SF_6 in the use stage was the main cause of the increased global warming impact of the E-beam disinfection system.

The strategies that can be used to improve the environmental weak points of the E-beam disinfection system, the

identified key issues, may include the replacement of SF_6 by a new refrigerant whose GWP ranges from low to nothing, and the redesign of the secondary winding and shielding facility perhaps through miniaturization of these parts. With these improvements, the E-beam disinfection system can be made comparable with the UV disinfection system and much more competitive than the ozone disinfection system in terms of environmental impact and energy consumption.

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